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# Report on INT Program 14-3: Heavy Flavor and Electromagnetic Probes

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## **Report on INT Program 14-3: Heavy Flavor and Electromagnetic Probes**

The Institute for Nuclear Theory program, Heavy Flavor and Electromagnetic Probes in Heavy-Ion Collisions (INT 14-3), was held 15 September to 10 October 2014. In addition to the four organizers: Ramona Vogt (LLNL and UC Davis), Peter Petreczky (BNL), Anthony Frawley (Florida State), and Enrico Scomparin (INFN Torino), the program was attended by 34 other participants spread out over the four week period. Almost all participants were recognized experts in the field and were invited to take part. Eight of the participants were postdocs and five were women.

There are two main thrusts to the study of heavy quarks and quarkonia in heavy-ion physics: “hot matter” (effects specific to the high temperature medium produced in heavy-ion or nucleus-nucleus collisions) and “cold nuclear matter” (effects that are present already in proton-nucleus collisions and are a baseline against which hot matter effects must be compared) as well as production of the heavy quarks and quarkonium (bound states of heavy quark-antiquark pairs) in perturbative QCD. Unfortunately, due to last minute cancellations the topic of electromagnetic probes was underrepresented. While some of these involved unforeseen personal issues, others were related to the QCD town meeting that coincided with the first week of the program and to the beginning of classes at some universities.

The program was structured so that the first two weeks were generally devoted to hot matter, especially lattice QCD. The second half was devoted to issues related to production and cold matter effects. An intense 2.5 day workshop, from 29 September to 1 October, with participants from both areas, bridged the two halves of the program. Aside from the workshop days, the program consisted of one to two talks of at least an hour in the morning with time in the afternoon available for work, group discussion, and/or smaller collaborative discussions. Although a theory program, experimentalists attended throughout, giving talks on recent data and future facilities.

Alexander Rothkopf (Heidelberg University) gave the first talk, on calculating quarkonium spectral functions and static quark-antiquark potentials at  $T > 0$ , employing a novel Bayesian approach, see e.g. INT-PUB-14-046 and Fig. 1. His talk was the first of several that focussed on topics related to quarkonium spectral functions, including Olaf Kaczmarek (Bielefeld), Clint Young (Minnesota), Chris Allton (Swansea), Seyong Kim (Sejong University), Yukimao Akamatsu (Nagoya), and Johannes Weber (TU Munich).

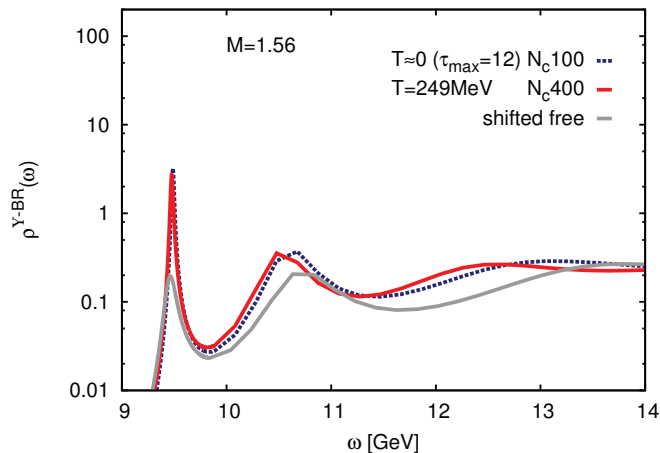


Figure 1: The  $\Upsilon$  spectral function for  $T = 249$  MeV and  $T = 0$  both reconstructed with 12 points in the time direction using the novel Bayesian approach.

Mike Strickland (Kent State) gave a talk on the theory of  $\Upsilon$  production in a quark-gluon plasma. His approach considers suppression in a viscous medium with a 2+1 hydrodynamic expansion. His results were consistent with the CMS  $\Upsilon(1S)$  measurement at midrapidity. However, the new results from the ALICE Collaboration, at forward rapidity ( $2.4 < \eta < 4$ ), show substantially more suppression than the CMS result which cannot be explained in his current approach. Ralf Rapp (Texas A&M) described the latest results on his two component approach to quarkonium suppression in a plasma including the cold matter effects of shadowing and nuclear absorption, plasma breakup by gluodissociation, and quarkonium regeneration. The plasma suppression is examined in both strong and weak binding scenarios. Anton Andronic (GSI) spoke about  $J/\psi$  production and suppression in the framework of the statistical hadronization model.

Manuel Calderon (UC Davis) gave the first experimental talk of the program, concentrating on  $\Upsilon$  production in STAR at RHIC and CMS at the LHC. While he discussed the AA data, his main focus was on proton-proton,  $pp$ , and proton (deuteron) on heavy target,  $p/d+A$ , collisions. He presented new STAR results from proton-proton,  $pp$ , and deuteron-gold,  $d+Au$ , collisions. The  $d+Au$  results suggest strong suppression of the  $\Upsilon$  yield at midra-

pidity. He also presented CMS results on the  $\Upsilon(2S)/\Upsilon(1S)$  and  $\Upsilon(3S)/\Upsilon(1S)$  ratios as a function of event activity. They quantified the  $pp$  and proton-lead,  $p+\text{Pb}$ , data in terms of ‘far’ activity (the transverse energy down the beam, at high pseudorapidity,  $|\eta| > 4$ ,  $E_T^{|\eta|>4}$ ) and ‘near’ activity (the number of tracks in the region of the  $\Upsilon$  measurement,  $|\eta| < 2.4$ ,  $N_{\text{track}}^{|\eta|<2.4}$ ). While there is a strong decrease as a function of the number of tracks near the  $\Upsilon$ , the decrease in the single ratios as a function of  $E_T$  is considerably weaker. The ratios are a stronger function of  $N_{\text{track}}^{|\eta|<2.4}$  in  $pp$  collisions than in  $p+\text{Pb}$  collisions even though there are a greater number of tracks in  $p+\text{Pb}$ . However, as also discussed in Torsten Dahm’s (TU Munich) talk, the slope is strongly dependent on which tracks are counted. This measurement will likely generate great theoretical interest.

There were several discussions, begun with Cesar da Silva’s (Los Alamos) talk but continuing throughout the program, about whether or not the nuclear modification factor  $R_{AA}$ , the ratio of production in nucleus-nucleus ( $AA$ ) collisions to the production in  $pp$  collisions, could be factorized into the  $pA$  ratios at forward and backward rapidity,  $R_{AA} = (\neq) R_{p\text{Pb}}(y) \times R_{p\text{Pb}}(-y)$ . Theoretically, it is true for cold matter effects and the data seem to bear this out as a function of rapidity. While Cesar focused more on the PHENIX d+Au results, Marzia Rosati (Iowa State) presented the PHENIX results in  $AA$  collisions.

To open our mid-program workshop, Helmut Satz (Bielefeld), who first proposed quarkonium suppression in a quark-gluon plasma, gave a personal view of where the field is today. He discussed two topics: how to tell if quarkonium is actually suppressed by the medium and a novel, new, approach to suppression. The first point is quite relevant: if open charm production is ‘suppressed’ the same way as the  $J/\psi$ , then is the  $J/\psi$  actually itself suppressed by color screening or is it just reflecting a similar mechanism as that affecting the more copiously produced open charm? The second part of the talk proposed that quarkonium suppression can be thought of as an emergent phenomena, as proposed by Verlinde and collaborators. If one compares the entropic force for quarkonium to the binding force or, similarly, the color screening radius of the medium to the bound state radius, then quarkonium will dissociate if the entropic force is greater than the binding force (or the screening radius is less than the binding radius), then quarkonium suppression is an emergent phenomenon. This is a work in progress.

We heard several on progress in understanding quarkonium production by

Bernd Kniehl (Hamburg), Jianwei Qiu (BNL) and Jean-Philippe Lansberg (IN2P3, Paris Sud). Bernd Kniehl spoke about his efforts to make a global fit of the NRQCD matrix elements for  $p_T > 3$  GeV, taking  $pp$ ,  $p\bar{p}$ ,  $\gamma p$ ,  $\gamma\gamma$  and  $e^+e^-$  data into account. While his fit gives a rather good description of these data, it has trouble reproducing the  $J/\psi$  polarization. (Other groups which take only  $pp$  and  $p\bar{p}$  data into account get different values for the NRQCD matrix elements as well as different polarizations.) Jianwei Qiu instead has tried to prove factorization of the NRQCD formalism. He has proven it at high  $p_T$ . Jean-Philippe Lansberg (IN2P3, Paris Sud) concentrated on calculations of the total cross section in the Color Singlet Model and NRQCD in his talk. He showed that if he took the numerical results from the groups fitting the NRQCD matrix elements at finite  $p_T$  and calculated the total,  $p_T$ -integrated  $J/\psi$  cross section at  $y = 0$ , the total cross section was significantly overestimated, especially at lower  $\sqrt{s}$ . His results suggests that the NRQCD matrix elements are not universal and factorization fails at low  $p_T$ . This is not inconsistent with the results described in the other talks.

During the program there was also considerable discussion of open heavy flavor dynamics and electromagnetic probes. Experimental heavy flavor results were presented by Andrea Dainese (Padova). Derek Teaney (Stony Brook) described next-to-leading order calculations of the photon rate and the energy loss coefficient  $\hat{q}$ . Swagato Mukherjee (BNL) presented lattice QCD calculations of deconfinement of charm mesons and baryons in terms of flavor correlators. Mikko Laine (Bern) talked about the heavy quark equilibration rate. Olaf Kaczmarek also discussed lattice calculations of the heavy quark diffusion constant. The limitations of Langevin dynamics for open heavy flavor energy loss was discussed by Santosh Das (Catania). Phenomenological transport approaches to heavy flavor suppression were described by Joerg Aichelin (Nantes) and Shanshan Cao (LBNL) while Elena Bratkovskaya (Frankfurt) described her results on electromagnetic probes.

Enrico Scomparin (INFN Torino) discussed the ALICE Collaboration results from  $p$ +Pb collisions. In particular, he discussed  $\psi(2S)$  production at forward and backward rapidity. At backward rapidity, they find significantly larger suppression than for the more strongly bound  $J/\psi$ , see the left-hand side of Fig. 2. Elena Ferriero (Santiago de Compostela) discussed how this effect could be accounted for by a large  $\psi(2S)$  comover cross section. The ALICE results on Pb+Pb collisions were presented by Roberta Arnaldi (INFN Torino). As described by Torsten Dahms (TU Munich), the CMS Collaboration has also shown results for the  $\psi(2S)$ , but in Pb+Pb col-

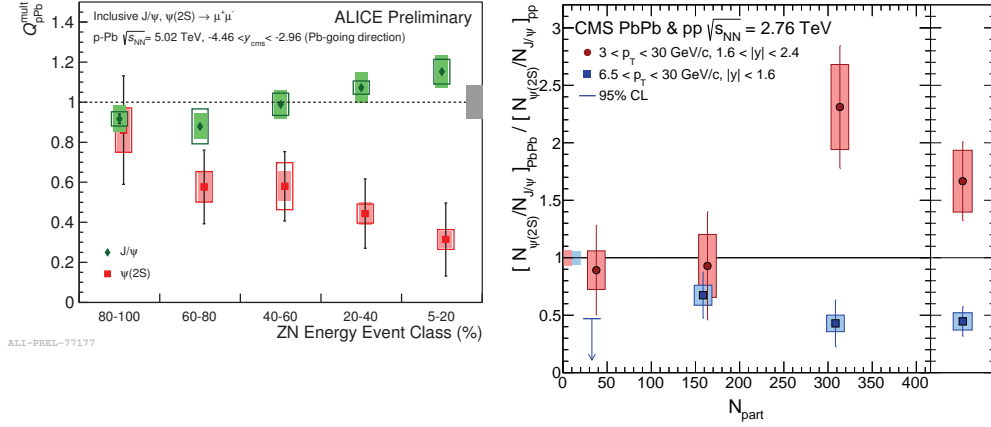


Figure 2: (Left) The nuclear modification factor  $Q_{pPb;mult}$  for the  $J/\psi$  and  $\psi(2S)$  states at backward (Pb-going) rapidity, measured by ALICE, as a function of the centrality of the  $p+Pb$  collision (0-20% corresponds to most central events). (Right) The ratio  $\psi(2S)/J/\psi$  for Pb+Pb collisions, normalized to the same quantity in  $pp$ , plotted as a function of  $N_{part}$ . The results are presented for two different  $p_T$  ranges. The right-most points correspond to the centrality-integrated sample.

lisions, where, although in a different kinematic region (central rapidity and transverse momentum larger than 3 GeV/c) they find an enhancement of the yields compared to  $J/\psi$ , shown on the right-hand side of Fig. 2. A consistent interpretation of these data poses nontrivial problems and although a final consensus did not emerge, interesting ideas such as large regeneration of  $\psi(2S)$  in the medium created in Pb+Pb collisions were debated and will surely form the basis of future theory and phenomenological studies. They also suggested to the experimentalists new measurements to be performed in the forthcoming LHC run.

Several experimental talks looked to the future with two talks on proposed experiments and two talks on future facilities.

Tony Frawley (Florida State) spoke on a revamping of the PHENIX detector into sPHENIX which would shift the focus of the detector to jet reconstruction and  $\Upsilon$  measurements. The current configuration of PHENIX does not allow separation of the three  $\Upsilon$   $S$  states but this would be possible in sPHENIX. Gianluca Usai (INFN Cagliari) spoke about a possible new fixed-target experiment at the CERN SPS, NA60+, which would improve upon

the old NA60 experiment by compressing the muon spectrometer while enlarging it in the transverse direction as well as adding a vertex spectrometer in front. They would employ proton and lead beams with energies from 20 to 160 GeV/nucleon. They could probe the region where deconfinement is expected to set in through electromagnetic probes, the first dilepton experiment that could address this energy regime. The NA60 dilepton statistics would be increased by a factor of 100. High statistics quarkonium measurements are also foreseen for  $p_{\text{lab}} > 60$  GeV.

There were two talks on possible future facilities. Andrea Dainese (Padova) gave a talk on work in the CERN study group on the Future Circular Collider (FCC). There is a series of ongoing workshops to present the physics case for a collider with a circumference of 80-100 km that the LHC would feed into. The collider would have energies of up to four times higher than those of the LHC. Ion beams are part of the plan. Andrea discussed the physics case for this machine from an ion point of view and asked those who were interested to join one of the study groups or at least follow along. His talk was followed by one from Jean-Philippe Lansberg who spoke about the effort to organize a collaboration for a fixed-target detector, AFTER, at the LHC, taking a fraction of the LHC beam on target. Discussions are ongoing as to the location of such a detector since this would strongly influence the nature of the physics program. One of the topics of interest for the AFTER physics program is the nature of nonperturbative charm in the nucleon. The latest results on this topic were presented by Tim Hobbs, a new postdoc in the UW Physics Department.

The last few talks of the meeting were hotly discussed even though they were on ‘cold’ matter. The talks by Francois Arleo (Ecole Polytechnique) on energy loss in cold matter, Jianwei Qiu on an overview of cold matter effects, Jean-Philippe Lansberg on calculations of the total cross sections in the CSM, NRQCD and the CEM and Enrico Scomparin (INFN Torino) on quarkonium measurements by ALICE in  $p$ +Pb collisions were all at least 1.5 hours long. These talks were notable for the number of questions asked and the stamina of both the speakers and the audience. The open format of the INT allowed the models of quarkonia in cold nuclear matter to be thoroughly discussed and compared to data. This discussion was only possible because almost all the people involved in these studies in the community were present at the INT simultaneously. This fits well with the INT’s goal of bringing together subject matter experts and giving them time to discuss and collaborate in a relaxed atmosphere. As Enrico pointed out in his talk, almost everyone who

had provided the experiments with predictions for  $p$ +Pb collisions were in the room.

Finally, a few words on the general atmosphere during the program weeks. The organizers gratefully acknowledge the excellent level of support from the INT staff. They were always kind, careful and professional in addressing every issue that arose. The ample availability of office and meeting space for people to work and interact helped to create an atmosphere that was simultaneously relaxing and stimulating. The long discussions, both during the seminars and in the afternoons have been very fruitful and, given that the main experts in this area participated in the program, have helped shape the future studies in the field.